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DETECTION OF A CHANGE OF SLOPE IN THE SPECTRUM OF HEAVY MASS COSMIC RAYS PRIMARIES BY THE KASCADE-GRANDE EXPERIMENT

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Abstract. KASCADE-Grande is an extensive air shower experiment devoted to the study of cosmic rays in the $10^{16} \div 10^{18}$ eV energy range. The array comprises various detectors allowing independent measurements of the number of muons (N_μ) and charged particles (N_{ch}) of extensive air showers (EAS). These two observables are then used to study the primary energy spectrum, separating the events into two samples on the basis of the shower size ratio, corrected for attenuation in the atmosphere, $\ln N_\mu / \ln N_{ch}$. The two samples represent the light and heavy mass groups of the primaries. In the studied energy range, only the spectrum of heavy primaries shows a significant change of slope. The energy (estimated using the QGSJET II hadronic interaction model) of this feature is in agreement with the expectations of a rigidity-dependent knee feature.

Keywords: cosmic rays, energy spectrum, extensive air showers.

1. Introduction

Knee-like structures have been found in the spectrum of the light and medium components of cosmic rays in the $10^{15} \div 10^{17}$ eV energy range [1]. These kinks produce the overall feature in the all-particle cosmic ray spectrum known as the knee, which was discovered by Kulikov and Khristiansen more than fifty years ago [2]. Several hypotheses have been proposed ot explain the origin of this feature [3–5]. A first class of models attributes this spectral feature to astrophysical mechanisms. The most favoured scenario explains this radiation by galactic sources (e.g. Super Novae Remnants) and the spectral feature of the knee either by the limit of acceleration in galactic sources or by the limit of containment inside local magnetic fields. Both scenarios predict the knee of the primary spectrum at an energy in agreement with the measured energy and scaling, for different elements, with the atomic number. Alternative scenarios explain the knee by a change of the hadronic interactions originating the extensive air showers; these models predict an energy dependence of the knee on the primaries mass number. Both kinds of models predict that there should also be a knee-like structure in the energy spectrum of the heavy component of cosmic rays at about 10^{17} eV.

Experiments that have studied the knee in the last decade have focused on the $10^{14} \div 10^{16}$ eV energy range, and have therefore not been able to detect the change in the slope of heavy primaries. The KASCADE-Grande experiment was designed to address the problem of the iron-knee by studying cosmic rays in the $10^{16} \div 10^{18}$ eV energy range [6].

Measurements of the primary spectrum of at least two mass groups can only be obtained if the experiment has a high resolution for all the EAS components needed to reach this goal. In KASCADE-Grande, the observables used are the muon (N_μ) and charged particles (N_{ch}, defined as the sum of the electrons and muons in the shower) numbers in the EAS at detection level. The ratio between the number of muons and charged particles has been identified as a variable with enough resolution to separate (with less than 10 % contaminations) the two event samples.

The technique is briefly described and the results are presented. The energy scale of the results depends on the hadronic interaction model used in the EAS simulations (e.g. QGSJET II [7]), while the spectral features are always detected in the *electron-poor* event sample (e.g. a high value of the above-mentioned ratio) irrespective of the exact value used to separate the events.

2. The KASCADE-Grande experiment

The KASCADE-Grande detector is located on the North Campus of the Karlsruhe Institute of Technology, Germany (110 m *a.s.l.*). Two arrays are the main components of the experiment. The layout is shown in Fig. 1.

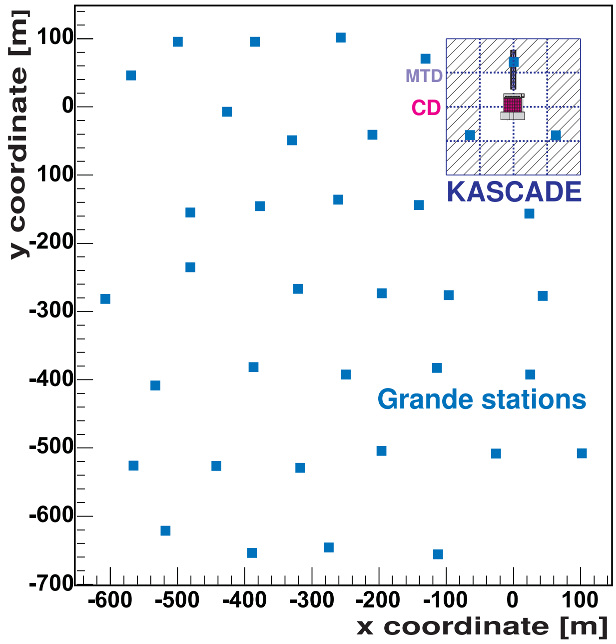

Figure 1. Experimental layout of the KASCADE-Grande experiment.

The first detector, called Grande, is $700 \times 700\,\mathrm{m}^2$ in area and uses $37 \times 10\,\mathrm{m}^2$ plastic scintillator detectors to sample the charged particle density at different distances from the EAS core. These measurements are used to estimate N_{ch}, the EAS arrival direction and core location. The second detector, i.e. the former KASCADE experiment array, comprises a 252 e/γ unshielded liquid scintillator and shielded μ plastic scintillation detectors. This array, covering a smaller ($200 \times 200\,\mathrm{m}^2$) surface, independently measures the muon number N_μ.

A complete description of the event reconstruction and of the achieved experimental resolutions can be found in [6]. In this short note, it is important to point out that N_{ch} and N_μ are detected with 15 % resolution and 25 % resolution, respectively.

3. Analysis and Results

The analysis was performed on a particular subset of data with zenith angles (θ) below 40°, with reconstructed cores in a fiducial area of $1.52 \times 10^5\,\mathrm{m}^2$ inside the central region of Grande and with shower sizes $\log N_{ch} > 6.0$ and $\log N_\mu > 5.0$. For these selection criteria, full trigger and reconstruction efficiency is achieved at an energy of $\log(E/\mathrm{GeV}) \geq 7.4$. The present analysis is based on 1173 days of data taking, for an exposure of $2 \times 10^{13}\,\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}$.

The analysis technique is described in detail in [8]. Using the Constant Intensity Cut method (CIC, described in [9]), the attenuation curves of N_{ch} and N_μ in the atmosphere are obtained, and can be used to calculate the equivalent particle numbers at a reference zenith angle ($\theta_{ref} = 21.5°$, selected as the mean

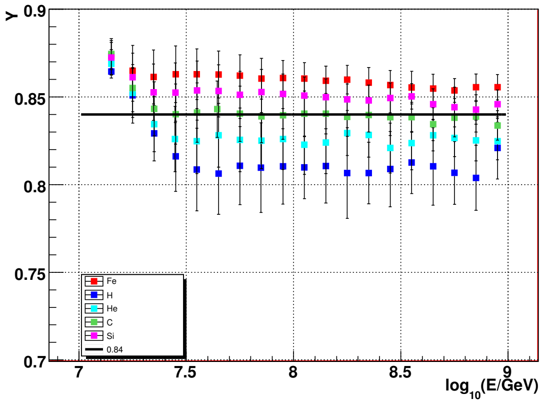

Figure 2. Mean values of Y^{CIC} for five primaries (from bottom to top: H, He, C, Si, Fe) vs. primary energy. Error bars represent the RMS of the Y^{CIC} distributions.

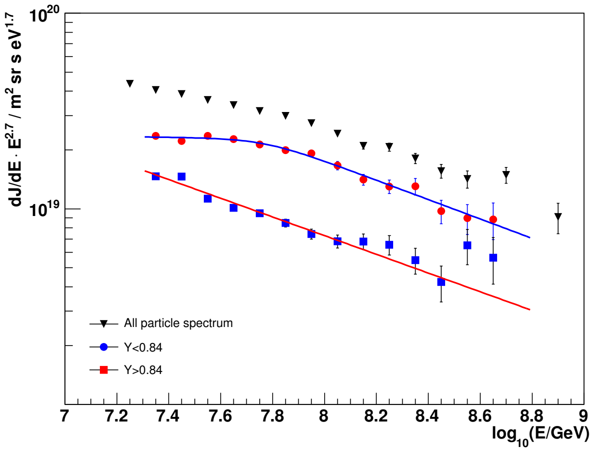

Figure 3. Reconstructed energy spectrum of the electron-poor and electron-rich components together with the all-particle spectrum for the angular range $0° < \theta < 40°$. The error bars show the statistical uncertainties.

value of the events zenith angle distribution). The CIC method allows the EAS propagation in the atmosphere to be taken into account in a model-independent way.

Having converted the measured $N_{\mathrm{ch}}(\theta)$ and $N_{\mu}(\theta)$ to the values at the reference angle, the ratio

$$Y^{\mathrm{CIC}} = \frac{\ln N_{\mu}(\theta_{\mathrm{ref}})}{\ln N_{\mathrm{ch}}(\theta_{\mathrm{ref}})} \tag{1}$$

is calculated. The values of the ratio Y^{CIC} for different primaries is then investigated using a full shower and detector simulation (sampling the primary energy on a power-law spectrum between 10^{15} and 10^{18} eV). The mean value of Y^{CIC} is almost energy-independent, and it increases with the mass of the primary nucleus, as shown in Fig. 2 (for a QGSJET II based simulation). Selecting events with $Y^{\mathrm{CIC}} \geq 0.84$, we separate the *electron-poor* and *electron-rich* ($Y^{\mathrm{CIC}} < 0.84$) samples. Heavy elements (Si and Fe) are representatives of the first group, and light elements (H and He) are representatives of the second. The fraction of misclassified events for protons and iron nuclei is lower than 15 % for energies above full efficiency, and does not depend on the reconstructed energy.

The primary energy ($\log(E/\mathrm{GeV})$) is attributed to each event following a procedure based on the N_{ch} and N_{μ} observables that is described in detail in [8]. The measured spectra of the light and heavy mass groups are shown in Fig. 3. It can easily be observed that the spectrum of the heavy component shows a clear knee-like structure [8]. Fitting the spectrum with a broken power-law expression [8], the change of the spectral slope is $\Delta\gamma = -0.48$ from $\gamma_1 = 2.76 \pm 0.02$ to $\gamma_2 = 3.24 \pm 0.05$, with the break position at $\log(E/\mathrm{GeV}) = 7.92 \pm 0.04$. The statistical significance of this change of slope is 3.5σ. However it should be pointed out that the light component of cosmic rays is still present at energies between 10^{17} and 10^{18} eV, though its relative abundance is smaller than that of the heavy component.

4. Conclusions

Applying a cut based on the ratio between the muon and charged particles numbers (calculated at a reference zenith angle), the KASCADE-Grande experiment is able (due to its unprecedented resolution in this energy range) to separate the measured events in samples generated by light and heavy primaries. The energy spectra of both components was measured; the energy spectrum of the heavy mass group shows a knee-like feature at an energy of $\sim \log(E/\mathrm{GeV}) = 7.92 \pm 0.04$. This primary energy value depends heavily on the hadronic interaction model used for the shower simulation, e.g. QGSJET II; while the knee-like structure in the spectrum is detected for different cut values of Y^{CIC} (i.e. different hadronic interaction models). The spectral steepening occurs at an energy where the charge-dependent knee of primary iron is expected, when the knee at about $3 \div 5 \times 10^{15}$ eV is assumed to be caused by a decrease in the flux of primary protons and/or Helium nuclei.

Acknowledgements

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